Determining strength limits for standing tree stems from bending tests

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Abstract

Non-destructive tests are essential in urban tree risk assessment. One of the commonly used methods, the pulling test method, relies on wood properties derived from testing small clear samples of green wood. In the past, such data had been suspected to overestimate the strength of intact tree trunks. Here we propose and test a novel method to measure the limit of proportionality directly in large standing trees. Material properties determined in tests on small specimen were not correlated with tree strength derived by testing entire tree stems. Thus, it is important to test strength thresholds on entire tree stems using the new field method described here. Furthermore, we show that stiffness measured during non-destructive pulling tests is a good indicator for yield strength in bending.

Keywords: proportional limit, pulling test method, bending test, *Acer pseudoplatanus, Fraxinus excelsior*

Introduction

The ability of trees to withstand forces exerted by factors like wind, snow and ice is essential in tree risk assessment with regard to public safety (Smiley et al. 2012). The stability of trees must also be addressed when they are used as supports in manmade structures like tree houses or adventure courses (cf. EN 15567-1). Currently, results from material tests on small-scale samples are often used to draw conclusions on the strength of stems and branches (e.g. Petty and Swaine 1985). This procedure was rarely verified (e.g. Brüchert et al. 2000), and when it was, significant discrepancies have been found (e.g. Kane and Clouston 2008). FOREST Gales uses knot factors to estimate stem strength from material properties derived from small samples (Gardiner et al. 2000). Lately, Ruel et al. (2010) examined similar knot factors by testing the actual strength of fresh cut logs of conifers in three-point bending. Yet, any direct proof of a stem’s strength will unavoidably involve its destruction.

The non-destructive pulling test method was developed for the assessment of safety against stem rupture and uprooting of urban trees in the late 1980’s (Sinn and Wessolly 1989). In order to assess stem strength, the results of bending the stem at low load levels are extrapolated within the elastic range to a species specific limit of elasticity (Wessolly 1991). The guideline values currently used in the pulling test method were also derived from testing small blocks of green wood (Wessolly and Erb 1998). The number of tree species listed in those tables is limited mainly to Northern European taxa. Material properties for green wood of worldwide occurring species are available from several other sources (Lavers 1973, Jessome 1977, Kretschmann 2010). But those reference values rarely allow for an application in the pulling test method as they usually refer to ultimate strength. Only Jessome (1977) provides data for strength at the limit of proportionality (PL), beyond which plastic deformation occurs (Niklas and Spatz 2012). Wood shows a gradual transition from elastic behavior to plastic deformation when critical loads are exceeded (Bodig 1982). The deviation from the proportional correlation between stress and strain according to Hooke's Law marks the end of any linear extrapolation and is an indicator for the overloading of structure (Gordon 1991).

The pulling test method uses PL as a threshold for strength. This species-dependent property is required to be able to extrapolate from a non-destructive test to stem resistance against fracture. To our knowledge, this property has not been measured in standing trees before. Therefore, we tested a new method for identifying PL by breaking standing trees and deriving strength properties for entire tree stems. We tested the applicability of data on flexural stiffness of tree stems gathered in a non-destructive pulling test as indicators for stem strength. We also tested if estimating the strength at PL may also allow for an assessment of the ultimate strength of tree stems.

A field method to determine the bending moment required for a standing tree stem to exceed the limit of proportionality

The field method was first tested on 10 London Plane trees (*Platanus acerifolia*) in Shalerville, OH, in 2010. The method was replicated on forest trees of two other species (*Acer pseudoplatanus* and *Fraxinus excelsior*) in Göttingen, Germany. Measurements were carried out with two inclinometers and one forcemeter of the TreeQinetic System (argus electronics GmbH, Rostock, Germany). During the test, a lateral force is applied at the stem at roughly half tree height. A forcemeter is positioned in the middle of the rope and the force is applied by a manual winch (e.g. Tirfor 1.6 t). In order to monitor the bending response of the tree, one inclinometer is placed at the base of the stem, the other at a height of 4 to 5 m. Force and inclination are recorded while the tree is pulled to ultimate failure.

The lower inclinometer monitors the inclination of the root plate. The inclinometer higher at the stem records deflection angles due to both root plate tilt and stem bending. The difference between the two inclinometer readings (Δ_N) is a measure for the deflection of the stem due to bending. Within the elastic range, Δ_N will increase proportionally with the applied base bending moment (BBM) according to Hooke's Law. As soon as PL is exceeded, stem deflection will increase at a greater rate than the applied load. A deviation of 2% from the expected linear values for stress or strain was chosen to determine PL in bending (cf. Burgert et al. 2003).

For two species, BBM at PL and at ultimate stem fracture were determined. There was a strong correlation between BBM at PL and at ultimate failure with significant differences between the two species (Figure 1).

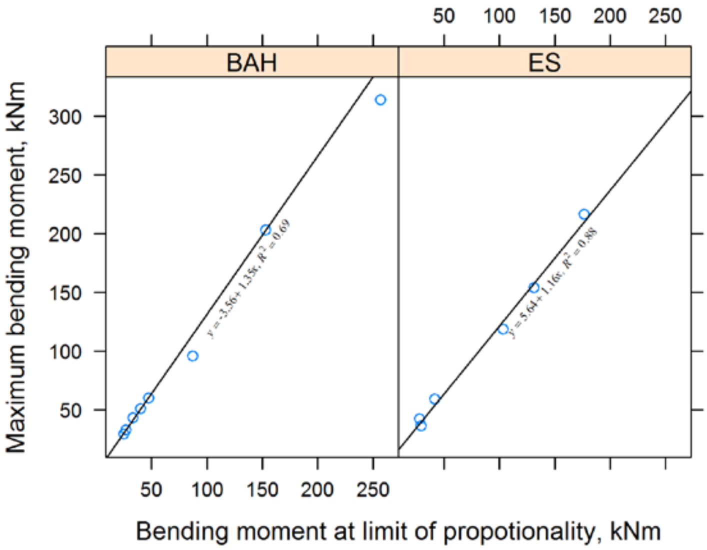

Figure 1-Correlations between bending moments at limit of proportionality and maximum bending stress in *A. pseudoplatanus* (BAH) and *F. excelsior* (ES) were highly significant.

Correlations between critical loads at the proportional limit and flexural stiffness measured in non-destructive pulling tests

In the pulling test method, strains in marginal fibers are measured with strain gauges that record the compression or elongation between two metal probes placed in the wooden body (Elastometer or Dilatiometer). At the same time, the lateral force applied by a mechanical winch is measured with a forcemeter (Brudi and Wassenaer 2002). During this procedure, irreversible damages due to overloading must be prevented. Therefore, tests are aborted well below a typical yield strain. Data gathered is used to assess the load required to exceed PL in bending. The validity of currently used thresholds for the extrapolation has not been scientifically tested for a greater number of trees.

In the present project, all trees were also tested non-destructively before pulling to ultimate failure. In this initial test, compression or extension in marginal fibers was measured with Elastometers (TreeQinetic System, see above) placed on defined positions on the compression or tension side of the tree stems. To measure within the elastic range of green wood, strains beyond 1,250 $\mu\varepsilon$ were prevented. Simultaneously, the applied force was measured with a Forcemeter (TreeQinetic System, see above) and translated into bending moment at the stem base (BBM), taking into account anchor point height and rope angle.

The slope of a linear regression of BBM on strain is a measure of the flexural stiffness of the stem. This property was tested as an indicator for the BBM at which the PL would de exceeded. According to the statistical analysis, non-destructive strain measurements on standing tree stems are a suitable indicator for BBM at PL (Figure 2).

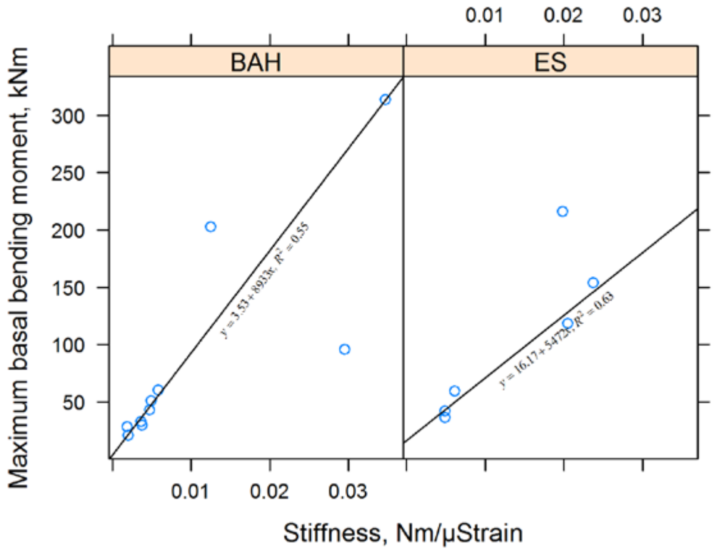

Figure 2-Stiffness of stems in non-destructive bending tests correlated closely with bending moments at failure in *A. pseudoplatanus* (BAH) and *F. excelsior* (ES).

Validating the field test results under lab conditions

The field test method was replicated under lab conditions on 10 almost straight stems of 30 year old *A. pseudoplatanus*. Trees were selected in a forest stand near Göttingen, Germany. They were harvested in January 2013 in a period of continuous subzero temperatures and logs of 6.5 m length were cut from the lowest part of the stem. The logs were immediately brought to the testing facility in Holzminden, stored in cold and moist conditions and tested within 7 days after harvesting. The testing apparatus was modified from standard protocols for four-point-bending (DIN 52186) to accommodate for testing entire logs of 6 m length and mid-diameters between 0.3 and 0.35 m. Two double-T steel beams formed the supports at a distance of 0.9 m around the middle of the stem. At the two ends of the stem low stretch slings were securely attached at a distance of 3 m from the stem center. Each sling was connected to a forcemeter and pulled upwards by two cranes. The speed was kept constant and stems were pulled until ultimate fracture occurred or the cranes reached their maximum capacity (50 kN).

The deformation of the stem was monitored using the TreeQinetic system. Two elastometers recorded compression in the marginal fibers on the top side of the stem. One Inclinometer was positioned at the lateral side of the stem under each support to determine the deflection of the stem from the original curvature. Those four sensors remained on the specimen until the test was terminated. Fiber strain on the tension side, i.e. on the underside of the stem, was recorded prior to the destructive test in the elastic range only and then removed for safety reasons.

PL was determined independently by three methods. For all logs, force was recorded over time as the cranes pulled the ends of the logs up at a constant rate. The force vs. time recordings initially show a proportional trend that turns into an underproportional increase after a specific force is exceeded. Furthermore, the correlation between compressive fiber strains and the mean of the two forces applied consists of a linear range beyond which strains increase overproportionally. A deviation from the proportional response could also be detected from the correlation between the inclination recorded by the inclinometers and the applied force. For all methods, PL was assumed when forces or deformations exceeded the value expected according to Hooke's law by more than 2%. The bending moments required to reach PL were independent of the three methods applied. The field method to determine PL is measurements. The results confirm that using two inclinometers on standing trees is a suitable procedure to determine BBM at PL.

9 out of 10 stems remained visibly intact while only one fractured before the test was aborted. Each stem was divided in 3 sections in order to differentiate between the parts between the two supports that experienced the greatest bending stresses (section 2) and the lowest and highest part of the stem. The latter were assumed to have been loaded well below the yield point according to the moment curve in four-point bending. From each section, a 0.6 m long disc were cut from all 3 sections and sealed with paraffin. A total of 2132 samples of 20 x 20 x 60 mm were cut and stored directly in a deep freezer. The position of each sample in the section was recorded. Later, samples were thawed and tested in the wet state under axial compression in an INSTRON testing device. MOE was measured in the elastic range over a length of 20 mm. Stress and strain at PL as well as ultimate stress were determined using displacement and force sensors. PL was set at 2% deviation from the theoretical elastic response.

Data published by Jessome (1977) indicates that the ultimate strength of green wood samples in axial compression explains variations of stress at PL measured in a three-point bending test (Figure 3). This could not be confirmed in our study. The ultimate compressive strength of 20x20x60 mm wood blocks was not closely correlated to PL in bending of 20x20x300 mm beams extracted in the direct vicinity (Figure 4). This discrepancy may result from the fact that Jessome (1977) lists mean values derived from several individual trees whereas we only compared wood samples cut from the same log.

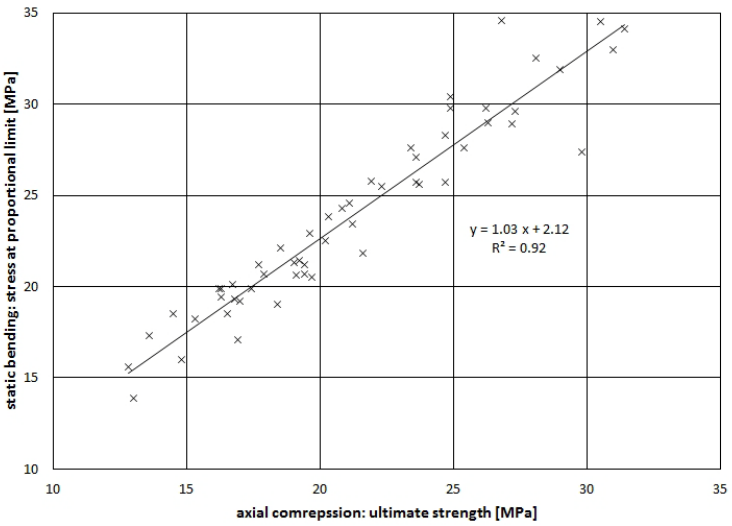

Figure 3-Ultimate strength of green wood samples in axial compression explains variations of stress at PL measured in a three-point bending test in data from Jessome (1977) for 54 species.

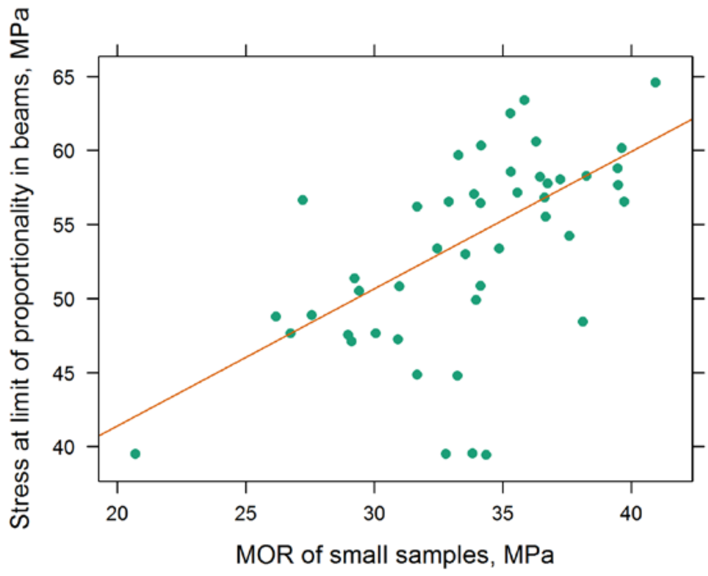

Figure 4-Stress at PL in bending beams of defect free wood of *A. pseudoplatanus* correlated loosely with ultimate strength in axial compression of small samples.

We also found that ultimate stress in compression for small blocks cut from unloaded sections of the stem could not explain variations in stem yield strength at PL (Figure 5). Therefore, it is necessary to investigated how material properties derived from testing small specimen in compression can be used to determine critical loads in entire tree stems (cf. Ruel et al. 2010).

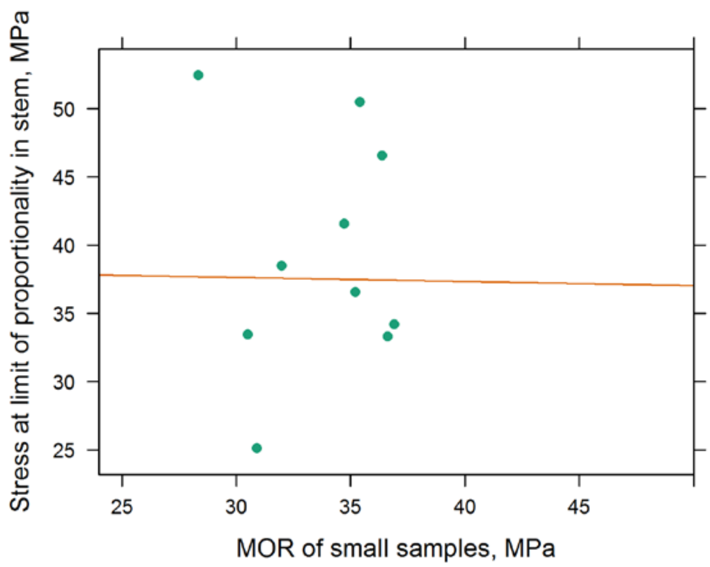

Figure 5-Average strength in axial compression of small clear samples was not correlated with stress at proportional limit of stems in *A. pseudoplatanus*.

Conclusions

It is possible to determine the limit of proportionality in a destructive winching experiment on standing trees by measuring applied forces while monitoring stem deflection with two inclinometers. If strain was previously recorded in marginal fibers during a non-destructive pulling test, critical strains can be derived by this procedure. Stiffness measured during non-destructive tests is a good indicator for yield strength. Material properties determined in tests on small specimen are less relevant for assessments of tree strength than values derived by testing entire tree stems. Thus, it is important to test strength thresholds on entire tree stems using the new field method described here.

Acknowledgements

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